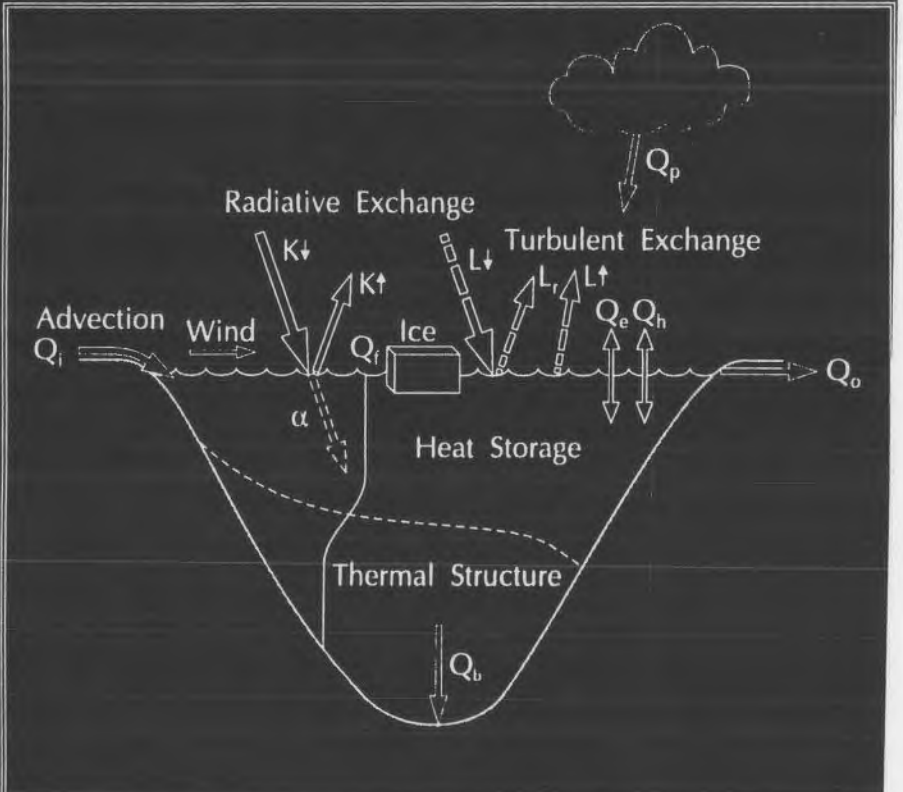
POTENTIAL CLIMATE CHANGE EFFECTS ON GREAT LAKES HYDRODYNAMICS AND WATER QUALITY



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Chapter 4
LARGE-SCALE CIRCULATION

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ABSTRACT : *Large-scale circulation is strongly related to the annual cycle (Sections 4.1 and 4.2). There are also other important influencing factors such as wind, water temperature and bathymetry. Short-term effects such as storm surge, surface seiche and coastal upwelling have been successfully modeled with these factors (Section 4.3). It was found that weather forecasts can be used in predicting the three dimensional, large-scale circulation for Lake Erie on a daily basis. Long-term effects, such as seasonal and interannual patterns are more difficult to predict because of the limited input information and the lack of reliable weather or climate forecasting techniques. Some attempts at long-term modeling analysis have led to a good understanding of seasonal patterns (Section 4.4). For example, preliminary results, either using Global Circulation Models (GCM's) or data from extreme warm or cold years, showed that prolonged stratification would increase the duration and magnitudes of the density-driven current. However, more studies and data are required to confirm these results (Section 4.5).*

4.1 INTRODUCTION

Understanding the mechanisms and variability of circulation in large lakes is one of the major goals of physical limnology. It is also important for biogeochemical sciences because knowledge of the transport of nutrients and contaminants is necessary for understanding how ecosystems function (see Chapter 7 for more detail).

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Significant progress in lake hydrodynamics during the last several decades is reflected in several reviews (Mortimer, 1974; Imberger and Hamblin, 1982; Hutter, 1984; Gray, 1986; Boyce et al., 1989; Schwab, 1992; Murthy and Schertzer, 1994) and monographs (Simons, 1980; Csanady, 1984). Nevertheless, important questions remain because of limited observations, especially long-term observations, and because of the limitations of current computer models, which do not explicitly include all significant physical processes of different spatial and temporal scales. This complexity is due to the fact that lake circulation is a product of many forces acting both on the lake surface and its boundaries: momentum and heat fluxes, atmospheric pressure, river inflow and outflow, and lake volume changes due to hydrological factors. These forces produce water movements in the lake with spatial scales ranging from millimeters to hundreds of kilometers (basin scale), and temporal scales from seconds to thousands of years (the scale of the lake's history).

The importance of various driving forces depends partly on the temporal scale. Momentum and heat fluxes are the dominant factors on time scales from days to seasons, while the hydrologic balance is important on longer time scales; like in the case of slow but persistent changes in the level of the Aral Sea. In this chapter we will discuss time scales ranging from the daily changes in weather to seasonal and interannual variability. We will also discuss the possibility of prediction on longer time scales. Historically, the focus of physical limnology was on short-term processes such as water level fluctuations due to seiches or storm surges. The obvious practical importance of these phenomena stimulated development of mathematical models, improvement in meteorological observations, and finally made possible prediction of hazardous floods. With respect to potential climate change, study and prediction of long-term fluctuations in lake circulation becomes important, since variations in wind stress, heat flux, or hydrological balance will cause changes in the lake's thermal structure and circulation, and eventually influence the whole ecosystem.

Progress in lake circulation studies generally reflects advances in the oceanic and atmospheric sciences. As in oceanic and atmospheric sciences, lake studies advanced from episodic observations to long-term specialized experiments such as IFYGL (Aubert and Richards, 1981), monitoring systems as CoastWatch (Schwab et al., 1992), and nowcast/forecast systems as the Great Lakes Forecasting System (Schwab and Bedford, 1994). Unfortunately, the comparison stops here because there has not been a coordinated limnological program with the goal of studying long-term climate-forced changes in the thermal structure and circulation in the Great Lakes, similar to such atmospheric/oceanographic programs as TOGA whose goal was to study seasonal-to-interannual variability and predictability of ocean-atmosphere system in the tropics (Hayes et al., 1991), or WOCE whose goal is to study interannual variability of the ocean circulation and its role in climate change (Wunsch, 1994a, 1994b). Therefore, one of the goals of this chapter is to emphasize the need for the development of such a program for the Great Lakes.

Although the focus in this chapter is primarily on modeling, mathematical formalism is set aside to emphasize physical aspects of lake hydrodynamics. Mathematical aspects of lake circulation can be found in other publications (Simons, 1980; Csanady, 1984; Hutter, 1984). Our goal is to provide a useful practical description of the important lake circulation processes that can reach a broad audience, including those with a background in aquatic biogeochemical sciences.

The outline of this chapter is as follows: in Section 4.2 we will provide a brief overview of the annual thermal cycle in the Great Lakes as a background for the discussion of lake currents. In Section 4.3 we will describe the main short-term physical processes and will demonstrate the state-of the-art in prediction of lake currents. In Section 4.4 we will present mean circulation patterns derived from modern observations, discuss progress in long-term numerical modeling, and also consider possible impacts of climate changes on lake circulation. Some prospects for the future will be presented in Section 4.5.

4.2 ANNUAL THERMAL CYCLE

Thermal stratification plays an important role in lake hydrodynamics giving rise to a variety of hydrodynamic phenomena from short-term internal waves to long-term density-driven currents. Therefore, we will briefly describe seasonal changes in the thermal regime of lakes before proceeding to current variability on shorter and longer time scales. More detailed information on the vertical thermal characteristics of large lakes can be found in Chapter 3.

Large temperate lakes exhibit a pronounced annual thermal cycle (Boyce et al., 1989). During the early winter, the lakes are usually vertically well-mixed from top to bottom at temperatures near or below the temperature of maximum density for freshwater, about 4°C. Further cooling can lead to inverse stratification, and ice cover. The Great Lakes are usually at least partially covered with ice from December to April (see Chapter 6 for more detail). Initially, ice begins to form in shallow bays and then gradually grows offshore. Maximum ice extent is normally observed in late February, when ice typically covers from 24% of Lake Ontario to 90% of Lake Erie (Assel et al, 1983). Ice thickness can vary from a few centimeters to a meter or more (Rondy, 1976). Ice melting and break up usually begins in March, when increasing solar radiation weakens the ice which can be more easily broken up by the action of wind and waves. Springtime warming tends to heat and stratify shallower areas first, leaving a pool of cold water (less than 4°C and vertically well-mixed because of convection) in the deeper parts of the lake. In spring, stratified and homogeneous areas of the lake are separated by a sharp thermal front, commonly known as the thermal bar (Tikhomirov, 1963). Depending on meteorological conditions and depth of the lake, the thermal bar may last for a period of from 1 to 3 months. Stratification eventually covers the entire lake, and a well-developed thermocline generally persists throughout the summer. In the fall, decreased heating and stronger vertical mixing tend to deepen the thermocline until the water column is again mixed from top to bottom. When the nearshore surface temperature falls below the temperature of maximum density, the fall thermal bar starts its propagation from the shoreline toward the deeper parts of the lake. Thermal gradients are much smaller during this period than during the springtime thermal bar.

4.3 SHORT-TERM VARIABILITY

Our definition of short-term variability is somewhat broader than usual because we will consider processes with periods from hourly-daily to intraseasonal. Longer time-scale processes will be considered in Section 4.4. We will also emphasize the most important basin-scale processes, eliminating short internal waves and capillary waves. Wind waves will be considered in Chapter 5, although we will briefly mention a wave model in Section 4.3.4. We will also omit tides because of their minor importance in lakes.

The vast majority of short-term physical processes in lakes are wind-driven. Because of their mid-latitude position, the Great Lakes are subject to periodic extratropical storms, particularly during the spring and fall periods when the jet stream is crossing these latitudes. Typical intervals between storms are 5-7 days during winter and 7-10 days during summer. Storms can rapidly generate strong currents which decay with time scales of several days. Keeping this in mind, we will start our description with the simplest physical processes that occur in a flat bottom lake of uniform density, and proceed to systems with stratification and topography.

4.3.1 Storm surges, seiches, upwelling, low-frequency waves, and eddies

4.3.1.1 Storm surge

When a steady wind blows along a channel, the equilibrium condition of the water surface in the channel is a depression of the water level on the upwind end and an elevation of the water level on the downwind end (storm surge). In a channel of uniform depth, the magnitude of the depression and elevation are the same and are proportional to the length of the channel, the square of the wind speed, and the inverse of the depth. In a real lake, this simple dynamic balance is modified by the earth's rotation, which causes the counterclockwise progression of the point of maximum water level displacement around the edge of the lake. Early studies of storm surges on lakes used the equilibrium condition (steady-state setup) to calculate water level deviations in the case of the constant depth (Keulegan, 1951), or taking account of depth variations by segmenting the lake along its axis and calculating equilibrium solutions for each segment (Hayford, 1922; Keulegan, 1953; Hunt, 1959). The results were generally quite good when the prevailing wind was close to a steady, uniform wind blowing along the main axis of the lake.

A more realistic approach was realized when the shallow water equations were used. This theory allows consideration of time-dependence and earth's rotation along with realistic lake shape when using numerical methods. In particular, Platzman (1958, 1963) performed such calculations for Lakes Michigan and Erie, and his results showed considerable improvement over the equilibrium method. Schwab (1978) added the effect of atmospheric stability and wind speed on drag coefficient to the time-dependence and two-dimensionality of the wind field. He also included the effect of land-lake wind speed ratio. The models of Schwab (1978) and Platzman (1965) now form the basis for routine operational storm surge forecast systems for Lakes Erie and Michigan respectively. Alternative approaches use a statistical regression relationship between storm surges and wind forcing (Harris and Angelo, 1963; Richardson and Pore, 1969). Some case studies of storm surges were described by Ewing et al. (1954), Donn (1959), Freeman and Murty (1972), Murty and Polavarapu (1975), Dingman and Bedford (1984), and Hamblin (1987). With increased computer power, three-dimensional models (Figure 4-1) are used for storm surge prediction (O'Connor and Schwab, 1994).

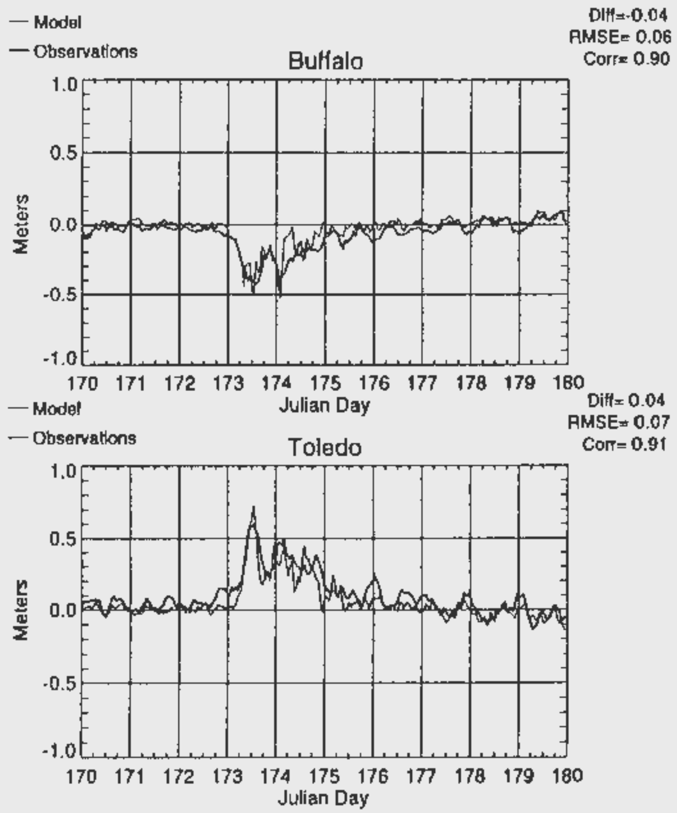

Figure 4-1. *Wind-induced barotropic lake response: Observed and modeled water levels at Toledo and Buffalo (O'Connor and Schwab, 1994).*

4.3.1.2 Surface seiche

Surface seiche is the response of the lake after wind cessation, or after an atmospheric pressure disturbance, when the initially wind- or atmospheric pressure-induced water level disturbance relaxes in the form of gravitational wave. Each lake has its own characteristic periods of oscillation for the fundamental (unimodal) seiche and higher harmonics. The period of the surface seiche depends on the size and shape of the lake and its bathymetry. The simplest model of seiches assumes that the lake can be approximated as a channel with seiche motions confined to the longitudinal axis of the channel. Platzman and Rao (1964a, 1964b) applied a one-dimensional, or channel, seiche model to Lake Erie, and compared the water level fluctuations with observations at standard water level gauging stations around the lake. Mortimer (1965) applied the channel theory to Lake Michigan proper and to Green Bay, and Rockwell (1966) calculated seiche periods for all five lakes using a one-dimensional model.

Some lakes, particularly Lakes Superior and Huron, have very complicated shorelines that cannot be approximated as a channel. In addition, the effects of the earth's rotation on seiching motions (which can significantly alter the structure of the longer period modes) cannot be fully accounted for in a one-dimensional channel model. Two-dimensional seiche, or normal mode, models were developed by Hamblin (1972, 1987), Platzman (1972), Rao and Schwab (1976), Rao et al. (1976), and Schwab and Rao (1977). These models have been able to accurately depict the two-dimensional structure and amplitude of lake surface oscillations for all the lakes.

4.3.1.3 Internal seiches and coastal upwelling

Internal seiches occur on the thermocline during the period of stratification when there is a density gradient between the upper and the lower layers. For internal seiches, volume transport in the upper layer at any point in the lake is very nearly compensated for by an equal and opposite volume transport below the thermocline, so that large fluctuations of the thermocline can occur without a noticeable change in the surface level. Internal seiches generally have longer periods than the surface seiches, and, therefore, are influenced more strongly by the earth's rotation. In off-shore areas they can appear in the form of Poincaré waves. Poincaré waves are a basin wide response with oscillations in the thermocline across the entire lake (Mortimer, 1974). The lowest order Poincaré wave has maximum wave amplitudes on opposite sides of the lake, with a node at the center. Poincaré waves are characterized by anticyclonic phase progression, and their period is slightly less than the inertial period. Schwab (1977) developed a numerical model to calculate the structure of the internal modes of oscillation in Lake Ontario. When non-linearity is strong, the internal seiche propagates like a steep front or internal bore. Simons (1978) calculated the propagation of an internal bore in Lake Ontario and compared his calculations with observations obtained during the IFYGL.

During the period of stratification, significant wind events will cause upwelling of the thermocline along the shore. Upwelling generally occurs on the upwind shore and the shore to the left of the wind direction, as discussed by Csanady (1968). These wind forcings, either directly or through Ekman drift (which for the Northern Hemisphere, moves water to the right of the wind due to the Earth's rotation), move surface water away from the shore so that it must be replaced by colder upwelled water. For example, in Lake Michigan, because of its north-south orientation, upwelling along the eastern shore results from northerly winds, and along the western shore from southerly winds. This process can cause the nearshore lake temperature to decrease by as much as 11 degrees C in 6 hours (Mortimer, 1975). The scale of the offshore distance over which this upwelling takes place depends on the wind stress and near-shore bathymetry, and is typically on the order of 5-10 km. An example of extreme upwelling of colder water that covered the eastern third of Lake Michigan after three days of northerly winds (Figure 4-2) is given by Ayers et al. (1958).

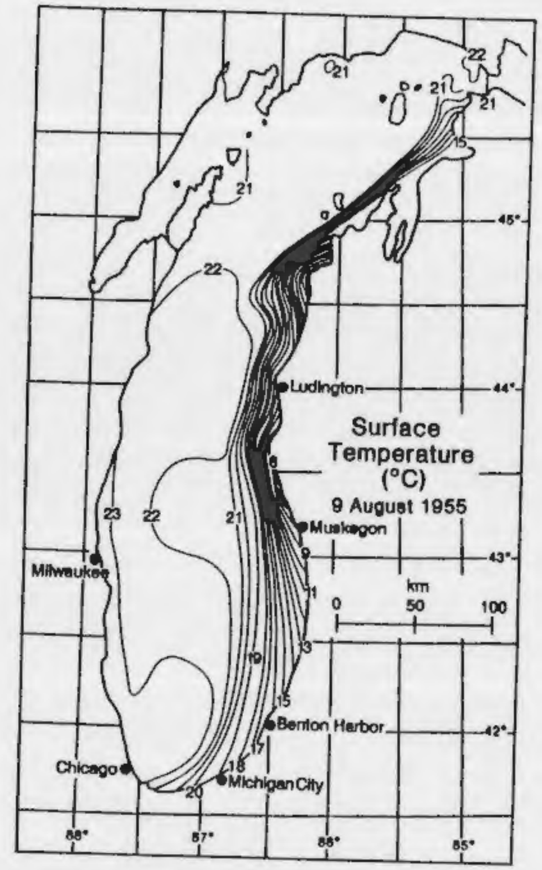

Figure 4-2. *Wind-induced baroclinic lake response: Surface temperature in Lake Michigan, 9 Aug 1955 (Ayers et al., 1958).*

The balance of forces in the region of upwelling is between the wind stress, Coriolis force, and internal pressure gradient. When the wind subsides, a new balance of forces must be established. If the bottom is flat, this results in two types of free internal waves: the previously discussed Poincaré wave and the Kelvin wave. The internal Kelvin wave is a coastally-trapped response of the thermocline that progresses cyclonically around the lake. The offshore scale of this wave is characterized by the so-called Rossby deformation radius which is the e-folding scale for the amplitude of this wave as a function of distance from the shore. For mid-latitude lakes the Rossby radius is 3-5 km. The Kelvin wave period is generally much greater than the inertial period. Schwab (1977) calculated the internal free modes of oscillation in a two-layer model of Lake Ontario assuming uniform equivalent depth. The lowest frequency mode was an internal Kelvin wave with a period of 25 days.

It has been observed that when strong wind events cease, the region of upwelling progresses cyclonically around the lake, either in the form of the internal Kelvin wave or as a thermal front. This was first observed by temperature observations at municipal water intakes for cities around Lake Michigan (Mortimer, 1963), and simulated later by Beletsky et al. (1997). Kelvin waves and thermal fronts were also found in other large lakes: Lake Ontario (Csanady and Scott, 1974; Csanady, 1977; Simons and Schertzer, 1987), and Lake Onega (Beletsky et al., 1994). Some indications of upwelling and thermal front progression have also been observed in satellite infrared imagery of lake surfaces (Csanady, 1977; Mortimer, 1988; Bolgrien and Brooks, 1992).

4.3.1.4 Topographic wave

For lakes with sloping bathymetry, another important free wave response should be added: the topographic wave. Unlike the Poincaré and Kelvin waves where gravity is the restoring force, the topographic wave is a so-called vorticity wave that can exist only in the presence of both depth gradients and earth's rotation (Saylor et al., 1980). It is a barotropic response and is relatively insensitive to stratification. When a steady wind stress over the lake pushes surface water downwind, the water level at the downwind end of the lake rises, and the resultant pressure gradient causes a return flow in the deeper part of the lake under the Ekman surface layer. The resultant circulation pattern (if the lake bottom has relatively simple form, like a paraboloid for example) consists of two gyres having opposite rotation. When the wind stress diminishes or ceases, the rotation of the earth causes this two-gyre pattern to rotate cyclonically around the lake with a characteristic period that depends on the basin bathymetry and the latitude. Typically, this period is several days. Analytical models were developed for basins with simple bathymetries by Lamb (1932), Ball (1965), Csanady (1976), Birchfield and Hickey (1977), Saylor et al. (1980), Mysak (1984), and Stocker and Hutter (1987). Numerical studies of topographic waves were performed by Schwab (1983). Resonant properties of topographic waves were studied by Simons (1983).

4.3.1.5 Mesoscale eddies

In addition to the basin scale motions, large lakes always exhibit smaller scale vortex motions known as mesoscale eddies. These eddies were observed in temperature fields in ship surveys (Boyce, 1977; Beletsky et al., 1994) and satellite imagery (Rao and Doughty, 1981; Mortimer, 1988). The size of these eddies range from several kilometers to several tens of kilometers. The most probable mechanism of eddy generation is barotropic or baroclinic instability of lake currents. An example of baroclinic instability of coastal currents was shown in the model of Rao and Doughty (1981).

4.3.2 Lake-wide circulation modeling

Large scale circulation typically has a complicated pattern because it is a product of many forces acting both on the lake surface and boundaries. Some of these forces undergo significant seasonal changes. In the absence of wind and density gradients (caused primarily by the heat flux), lake circulation depends on the hydraulic flow only, which seldom exceeds an amplitude of 1 cm/s over most of the lake. Hydraulic flow is probably most important in a fully ice-covered lake in winter. In the fall, when a lake is well mixed and density gradients are small, wind forcing should be added to the hydraulic flow, and it is typically at least of order of magnitude larger. In spring and summer, heat flux on a lake surface causes density gradients which can produce currents comparable to wind-driven currents, and which make lake hydrodynamics even more complicated. Typically, no analytical solution is available if one wants to study circulation in a lake with realistic bottom topography, no matter what kind of forcing is used. To deal with this problem, numerical models of lake circulation were developed.

Lake-wide circulation models have been developed since late 1950's as a supplement to scarce current observations in the Great Lakes. They evolved quickly from very simple models, based on the geostrophic relationship, to fully non-linear 3-dimensional models that form the basis of today's nowcast-forecast systems. One operational nowcast-forecast system, the Great Lakes Forecasting System, will be described later in this chapter. It is useful, though, to consider the development of the general circulation models because one can often see more clearly a particular hydrodynamic phenomenon in a simple model, while in a complex model it can be masked by the interplay of multiple factors. In particular, using simple models, we will demonstrate two major concepts that explain the existence of different circulation patterns in large lakes: density-driven (one-gyre) and wind-driven (two-gyre) circulations.

4.3.2.1 Dynamic height method

This is a simplest baroclinic (variable density) model based on the assumption of geostrophy, which means that the horizontal pressure gradients are balanced by the Coriolis force. The only information this model needs is a three-dimensional density field (in most cases temperature is sufficient) in the lake, in a part of the lake, or even on a vertical cross-section. First applied by Ayers (1956) to Lake Michigan circulation studies, this model quickly became so popular that it is probably difficult nowadays to find a large lake in the world with some temperature observations where this model has not been applied. The model is important conceptually because it explains the prevalence of a one-gyre cyclonic circulation pattern during the thermal bar period and full stratification period in many lakes. The point is that during these periods the warmest water is typically located nearshore, while the coldest water is offshore. This situation generates pressure gradients in the offshore-nearshore direction, and these gradients (in the absence of the wind) are balanced by the Coriolis force, which is directed to the right of the flow direction. Since the pressure gradient is directed offshore, the Coriolis force is directed onshore, and the current is directed alongshore with the coast to the right of it (in the Northern Hemisphere). Therefore, in a lake with simple bottom topography, like Lake Ontario, the circulation has a one-gyre cyclonic pattern (Fig. 4-3). What happens when the wind starts to blow? Obviously, in the case of a strong wind, the pressure gradients caused by the lake level gradients should be taken into account. In this situation we need a completely different class of models, the so-called barotropic models.

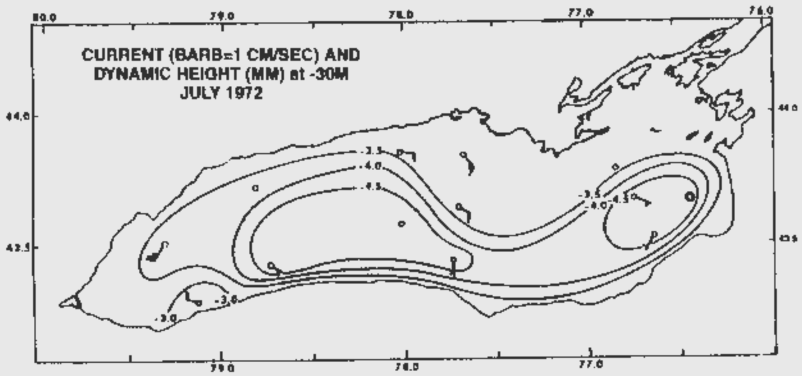

Figure 4-3. *Baroclinic one-gyre circulation: July 1972 dynamic height analysis and current observations, at 30 m depth in Lake Ontario (Pickett and Richards, 1975).*

4.3.2.2 Barotropic models

Barotropic models, as opposed to the dynamic height method, completely ignore density-driven currents, emphasizing the wind-driven ones. They also became quite popular because they need only wind information as an input, and do not take much computer time because they are vertically averaged, two-dimensional models. Initially, they were applied in their finite difference form to Lake Ontario (Rao and Murty, 1970), and other Great Lakes (Murty and Rao, 1970). As was stated previously in the section describing topographic waves, a horizontally uniform wind generates a two-gyre circulation pattern in a lake that has simple bathymetry (Figure 4-4). The theoretical explanation of this phenomenon was given by Bennett (1974). He showed that in the nearshore region, the wind stress is the dominant factor and the transport is in the downwind direction. In the deeper regions offshore, the pressure gradients (caused by the surface level gradients) generate transport opposite to the wind direction. Obviously, in lakes with complicated bathymetry, the circulation will consist of several cyclonic and anticyclonic gyres in the case of horizontally uniform wind.

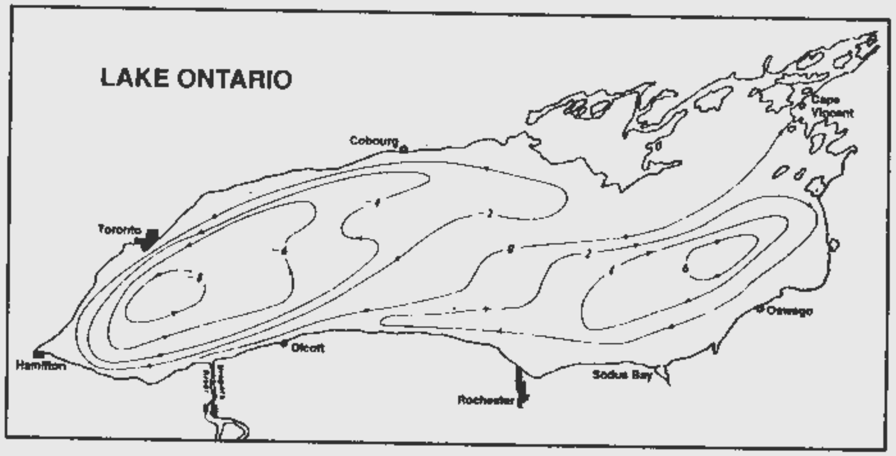

Figure 4-4. *Barotropic two-gyre circulation: Steady-state model transport lines (10^{10} cm^3 s^{-1}) in Lake Ontario for 5 m s^{-1} for northeast wind (Pickett, 1976).*

Another factor that can change the circulation pattern in the lake is wind vorticity. Because of the size of the lakes, and their considerable heat capacity, it is not uncommon to see lake-induced mesoscale circulation systems superimposed on the regional meteorological flow, a meso-high in the summer (Lyons, 1971) and a meso-low in the winter (Petterssen and Calabrese, 1959). There can also be a considerable amount of vorticity imparted to the lake by the normal circulation pattern of an extratropical storm as it passes over the lake. Any vorticity in the forcing field is manifest as a tendency of the resulting circulation pattern toward a single gyre streamline pattern, with the sense of rotation corresponding to the sense of rotation of the wind stress curl (Rao and Murthy, 1970; Hoopes et al., 1973; Strub and Powell, 1986). Besides the wind vorticity and topographically-induced vorticity, the vorticity of the main gyres in a thermally homogeneous basin depends on two other factors: a planetary vorticity (β-effect), and a bottom stress vorticity. It is traditionally considered that the most important factor overall is topography, although there are some indications that wind vorticity may be equally important. For example, it can be responsible for anticyclonic summer circulation in Lake Erie (Saylor and Miller, 1987).

4.3.2.3 Baroclinic models

The first baroclinic models approximated vertical structure as the superposition of two or more horizontal layers with impermeable interfaces (Kizlauskas and Katz, 1973). As computer power grew, so did the model complexity. In the early 1970's it became possible to construct 3-dimensional models that incorporated both thermally and wind-driven currents, although the parameterization of turbulent momentum and heat diffusivity was rather simple. Pioneering works of Simons (1973, 1974, 1975, 1976a, 1976b) created the basis for numerical studies of circulation and thermal structure in the Great Lakes. In particular, Simons was able to demonstrate some of the previously introduced concepts of wind-driven two-gyre circulations, and thermally driven one-gyre circulations in his numerical experiments with the Lake Ontario model. At approximately the same time, Bennett (1977) demonstrated the propagation of Kelvin waves, and also studied the effect of grid resolution on the wave speed. A lot of effort was put into model verification using direct current observations (Allender, 1977).

In the early 1980's the first 3-dimensional baroclinic models were applied to the largest European lakes: Lakes Ladoga (Filatov, 1983) and Onega (Beletsky et al., 1994). In many of these models, as well as in Simons (1976b) model, the density field was prescribed on the basis of observations, like in the dynamic height method. Therefore, they were useful only for diagnosis of circulation, not for forecasting. The horizontal and vertical resolution in early 3-d models was rather coarse: 5-10 km horizontal grid size, and 4-8 vertical levels. The majority of these models used constant coefficients for the horizontal turbulent diffusion of momentum and heat, and simple parameterizations of vertical viscosity and diffusivity.

The most recent 3-dimensional models are characterized by prognostic temperature schemes, sophisticated turbulence closure schemes, terrain-following vertical coordinates, generalized orthogonal horizontal coordinates, and increased horizontal and vertical resolution. For example, one such model, the Princeton model (Blumberg and Mellor, 1987) was recently applied to studies of Lake Erie circulation (O'Connor and Schwab, 1994) and also for the Lake Michigan studies (Beletsky et al., 1997).

4.3.2.4 Model accuracy and predictability

The important practical question about numerical models is how accurate are they? There are four sources of error in the modeling process: initial conditions, boundary conditions, model physics, and numerical truncation errors. We can expect significant improvement in model physics and numerical errors as the time goes on because of more sophisticated turbulence schemes, and increasing model resolution. We can also expect improvement in the specification of the boundary conditions because of the development of observational networks, and especially remote sensing methods. Initial conditions will always be a concern because it is impossible to specify exactly the 3-dimensional current and temperature field in a large lake. As Lorenz (1963) showed, even the smallest error in the initial condition of the atmosphere tends to grow larger in time because of the instability of the flow. This is the primary factor limiting the predictability of weather forecasts. One can expect the same type of behavior from the lake's "weather." There is a certain difference in the situation with lakes. During the periods of strong storms, lake currents are highly predictable, because they are essentially wind-driven currents. The studies of predictability of currents on the U.S. East Coast (Aikman et al., 1996) showed that in the nearshore regions, primarily wind-driven currents were highly predictable, while predictability was minimal for offshore currents because of the prevalence of Gulf Stream instabilities. Therefore, initial conditions might not be that important when atmospheric forcing is strong. Even after the cessation of strong winds, the currents still might be predictable for some time, because the circulation is dominated by such predictable periodic processes as Kelvin waves in summer or topographic waves in winter. In tropical oceanography, the progress in predicting El-Nino events is possible because of the prevalence of the Kelvin wave in the overall ocean response (Philander, 1990). It might be somewhat different during the periods of light winds, when baroclinic effects become more important, and lake circulation might be significantly less predictable. Obviously, more research is needed in this area.

4.3.3 Coastal zone modeling

Dynamics of the coastal zone are different from offshore areas because of one obvious constraint: net onshore and alongshore currents must vanish at the shore. This constraint leads to several interesting phenomena (Murthy and Schertzer, 1994). Firstly, the currents become increasingly alongshore-oriented as they approach the shore. Secondly, a so-called coastal boundary layer develops, where alongshore currents increase from 0 nearshore to a maximum at about 5-10 km offshore, and then decrease farther offshore. Thirdly, in summer, the strongest currents are frequently localized above the thermocline in a narrow nearshore zone. This strong current is called the coastal jet (Csanady and Scott, 1974). Here we will consider two different approaches to the prediction of coastal zone currents. The first employs current observations at different points, while the second employs numerical modeling.

4.3.3.1 Empirical models

It was noticed long ago that nearshore currents depend heavily on wind forcing. At the same time, their speed and direction cannot be derived from the condition of equilibrium between the wind stress and bottom friction because of the influence of topographic waves. While it is possible to predict these currents using conventional hydrodynamic models, there is another, sometimes more efficient method. This approach makes use of so-called impulse-response functions, which are calculated on the basis of current and wind observations. Once calculated, these impulse-response functions can be used for current predictions using only wind observations. Impulse-response function models were developed first for the storm surge modeling (Schwab, 1978), and later they were applied for Lake Ontario winter current calculations (Simons, 1984; Murthy et al., 1986). As these authors showed, they were able to predict up to 75% of the current variability with the impulse-response function model. Another empirical model was developed for summer coastal circulation (which is even more complicated because of the addition of Kelvin waves) by Bennett and Lindstom (1977).

4.3.3.2 Fine resolution coastal zone models

In the modeling of large lakes and estuaries, the numerical grid scales are usually on the order of several hundred meters to a few kilometers. The large scales are chosen to enable the organization of a numerical grid system to cover a large modeling space where the total number of grids can be kept reasonable. The coarse grid system possesses fewer numerical nodes and computation cells, thus requiring less computer memory and permitting more efficient computation. The scale is appropriate for large lake barotropic and wind-driven circulation studies, particularly in cases where boundary conditions are of a similar order of scale. However, the large scale is often too coarse for specific nearshore coastal zone applications. Localized coastal zone applications demand detailed hydrodynamic information that requires a fine resolution model.

The spatial resolution of a fine grid model is on the order of a meter to a few meters. To conduct a fine resolution modeling exercise, there are several unique difficulties and challenges. The least difficult among them is to design a closely spaced grid to match the physical boundaries such as coastal lines and bathymetry. This is often a tedious and time-consuming task. The more difficult challenge is to accurately and precisely set open boundary conditions with the necessary fine spatial and temporal scale. To provide the necessary dynamic boundary conditions precisely at the open boundary requires a careful and deliberate procedure to link a coarse grid model for the large lake hydrodynamic system, which simulates the hydrodynamic boundary conditions on a coarse scale, with a suitable transitional model to meet all the open boundary conditions of the fine resolution model. The linkage procedure of the coarse grid and fine resolution models includes the nesting of two- and three-dimensional finite difference or finite element models.

Leendertse et al. (1990) described the development of procedures to nest the two- and three- dimensional numerical models that were used to simulate flow conditions at the storm-surge barrier in the Eastern Schuldt of the Nétherlands when the storm surge barrier had only been partially constructed. The model sequence consisted of the main model and the submodels. The main model is a storm surge model for the whole estuary in which a grid size of 400 meters was used. Each submodel of the construction area of barrier sections was given boundary data from the main model of the whole estuary. Having the nested submodels separated from the estuary model kept the total number of grid points small enough to enable computer programs to run more efficiently. Also, modifications that represent a particular building phase of construction could be done without simulations involving the whole model. These features make the use of nested models efficient and attractive.

The fine grid nested model obtains its boundary conditions from the coarse grid main model. The currents and water levels at the two model boundary points are not matched because of the difference in modeling scale and emphasis. Leendertse et al. (1990) used the current distribution abstracted from the estuary model, which had a grid size of 400 m, to drive the nested model, which had a grid size of 45 m. It was found the abstracted currents contained insufficient detail and introduced significant error. The problem was resolved by inserting a transitional nested model which had a grid size of 90 m. The researchers also found that the velocity distribution at the open boundary seemed more likely to simulate correct currents than using water levels in the nested models.

Shen et al. (1995) developed a nested model approach to study the currents and pollutant transport in the nearshore area along the waterfront of the City of Toronto and the mouth of Mimico Creek in Lake Ontario. They used a 2 km grid for Lake Ontario, a 500 m grid for the Toronto waterfront, and a 100 m grid near the mouth of Mimico Creek. The depth grids and time steps were the same for all models. The fine grid model drew the open boundary conditions by interpolating velocities and water levels at the open boundary from those found in the coarse grid model.

The nested finite difference model with a uniform grid system has the advantage of keeping the number of grid points within computer limitations and using the fine grid size appropriate to suit the local applications. Each model step is built on a proven numerical scheme that can be processed efficiently within computer limits. However, the procedure to match coarse grid and fine grid boundary conditions at the open boundary should be carefully investigated. There could be significant error introduced into the submodels if the nested size transition is too drastic or the interpolation scheme is poor. Recognizing these difficulties, Lee et al. (1996) modeled the nearshore area of the City of Milwaukee in Lake Michigan using a fine resolution finite element model. The finite element grids at the open boundary were coincident with those on the coarse grid model. The element grid size in the outer layers of the fine resolution grids are gradually reduced. In this application, the grid size reduced from 1 km to 100 m and eventually to less than 10 m at the harbor facility area. The transition from the coarse grid to the fine grid was accomplished without interpolation. It was found that the numerical results were smoother if the elements in the transition layer gradually changed in size. It was also found that it was not necessary to use different bottom roughness in the fine resolution model to balance the transition as in the nested model case.

Separation of the coarse and fine grid models is an attractive approach to meet the physical demand for high resolution modeling in the nearshore area and the continuing interest and numerous requests for running complex simulation models using personal computers. We can limit the number of grid points by using a coarse grid model to simulate hydrodynamics in a large lake. We then use a fine grid high resolution model to concentrate on simulating the detailed hydrodynamic information necessary for environmental and pollution investigations or an engineering design and construction project in a nearshore coastal zone in the large lake. This approach has been demonstrated to be efficient, economical, and accurate.

4.3.4 Great Lakes forecasting system

In Section 4.3.2 we traced the development of lake-wide circulation models. So far, we have considered only research studies, because all models were used in a hindcast mode. Recent increases in computer power, coupled with the real-time availability of data from observing systems, now allows development of forecasting and prediction systems for the Great Lakes. This represents a significant step in the evolution of large lake modeling - from being used primarily as a research tool to applications involving operational, real-time forecasting. The Great Lakes Forecasting System (GLFS) is a real-time prediction system that was created for daily forecasting of surface water level fluctuations, horizontal and vertical structure of temperature and currents, and wind waves in the Great Lakes. Lake Erie is the first lake to be fully implemented in the system. The system uses surface meteorological observations and forecasts from numerical weather prediction models as input. Lake circulation and thermal structure are calculated using a three-dimensional hydrodynamic prediction model. Output from the models is used to provide information on the current state of the lake and to predict changes for the next several days. The system is also designed for hindcasting and scenario testing. The initial implementation of the system in 1993 and 1994 produced daily nowcasts of system variables for Lake Erie from April to December each year (Schwab and Bedford, 1994). In 1995, the system began to use mesoscale meteorological forecasts from NOAA's National Meteorological Center (NMC) Eta model to produce 24 hour forecasts of system variables.

4.3.4.1 System design

In the forecasting mode, a daily run is made for each lake. The model is run for 48 hours, beginning 24 hours previous to the forecast time, thus generating a 24 hour hindcast and a 24 hour forecast. A forecast period of 24 hours was chosen because it is a reasonable period for which mesoscale meteorological forecasts could be used with confidence and a period of interest to most Great Lakes users. Observed meteorological conditions are used to specify surface boundary conditions for the first 24 hours of the run. The current and temperature fields from the model at this point in the run are saved to be used as initial conditions for the next day's run. These conditions constitute the 'nowcast' of the present state of the lake. Since 1995, forecasts from NMC's Eta model (Black, 1994) have been incorporated into the system. The 29 km version of the Eta model provides reasonable resolution of the Great Lakes with 28 grid points over Lake Erie. Eta model output fields are obtained over the Internet from NOAA's Information Center. Forecasts of overlake meteorological conditions are used as boundary conditions for the second 24 hours of the run. The output of this part of the run constitutes the lake forecast. Marine meteorological data are obtained from the National Weather Service's (NWS) Cleveland Forecast Office for the nowcast portion of the run. The numerical models are run on the Ohio Supercomputer Center Cray Y-MP8/864 Supercomputer.

Figure 4-5 is a schematic diagram of the functional components of the GLFS. The primary data required to nowcast and forecast coastal circulation and thermal structure are (1) initial conditions for the current, temperature, and water level fields, (2) observations of overlake meteorological conditions for the last 24 hours, (3) forecasts of surface heat flux and wind stress for the next 24 hours, and (4) forecasts of lateral (inflow and outflow) boundary conditions. At present, there is no feedback from the circulation model to the atmospheric model for the short duration of the forecast.

4.3.4.2 CoastWatch

Great Lakes CoastWatch is a part of a NOAA wide program that was designed to provide near real-time access to satellite imagery, image products and *in situ* environmental data for U.S. coastal regions (Schwab et al., 1992; Leshkevich et al., 1995). Current CoastWatch image products are obtained several times a day from NOAA polar-orbiting weather satellites (NOAA 12 and NOAA 14) which each carry the Advanced Very High Resolution Radiometer (AVHRR). For the CoastWatch program, AVHRR data are mapped to a Mercator projection and presented as four scenes of the Great Lakes region. One synoptic scene covers all five lakes at approximately 2.6 km resolution. The other three scenes focus on Lake Superior, Lakes Michigan and Huron, and Lakes Erie and Ontario at twice resolution of the five-lake scene. Image products include surface temperature, visible and near-infrared reflectance, brightness temperature, satellite and solar zenith angle data, and cloud masks. Over 32,000 image products have been received and archived since 1990. In addition, *in-situ* and modeled data including marine and meteorological observations, and water level gauge measurements, are also routinely received and made available via dial-in modem or Internet. A new CoastWatch product is a cloud-free, composited surface temperature chart that will include an ice cover analysis overlay during winter months. The CoastWatch satellite imagery is currently used in the Great Lakes Forecasting System as verification data for nowcasts and forecasts of surface water temperature. In the future, it may also be used for assimilation of surface water temperature into numerical model and for estimation of surface heat fluxes.

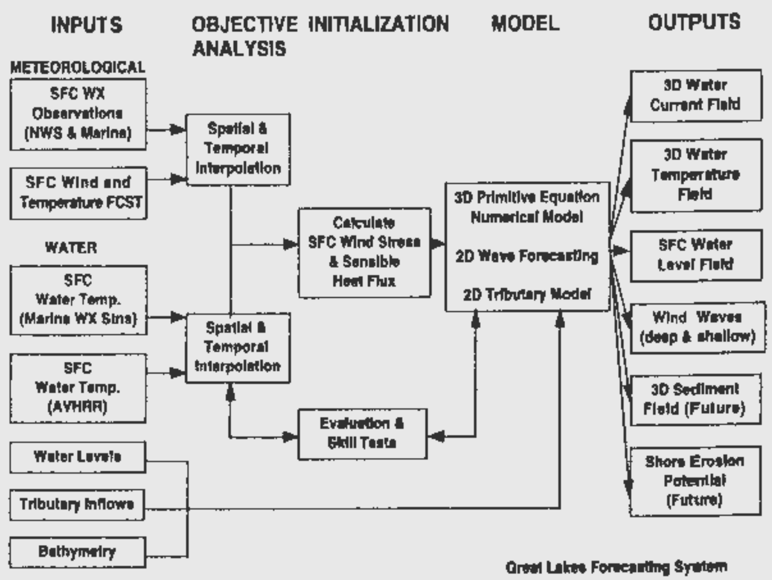

Figure 4-5. *Flowchart for operation of Great Lakes Forecasting System (Schwab and Bedford, 1995).*

4.3.4.3 Numerical models

As shown in the schematic in Figure 4-5, two types of models are currently used in the GLFS: 1) a numerical model for calculating velocity, temperature, and water level distribution, and 2) a wave model for calculating the wave height, period, and direction fields. The 2D tributary model is still under development. The numerical circulation model used in the GLFS is a three-dimensional ocean circulation model developed at Princeton University for coastal ocean applications by Blumberg and Mellor (1987) and subsequently adapted for Great Lakes use at NOAA Great Lakes Environmental Research Laboratory (GLERL) and Ohio State University (OSU). The model is driven by time-dependent surface boundary conditions for wind stress and heat flux. The physical parameters predicted by the model are the three-dimensional velocity distributions, the temperature field, and the free surface water level. The wave model (see Chapter 5, Section 5.2.6) used in the GLFS is a parametric model developed jointly at the Canada Centre for Inland Waters and GLERL (Schwab et al., 1984).

4.3.4.4 Products

Output from the numerical model consists of all relevant two-dimensional and three-dimensional fields at hourly intervals. The main products are a set of two-dimensional color maps of various fields predicted by the GLFS. These maps are generated each morning and represent the current state of the lakes and a 24 hour forecast. The maps include water surface elevation, wind speed and direction, surface water temperature, vertically averaged current, and wave height and direction. In addition, a time series plot of hourly water levels at three stations in the lake is produced to show the history for the last 5 days. A sample output map of wave height and direction, surface elevation, surface temperature, and vertically averaged current, is shown in Figure 4-6. This map is a nowcast for 12:00 EDT on June 8, 1994. The map products are stored in a computer-readable format for downloading via dial-in or Internet access to the OSU computer system (http://superior.eng.ohio-state.edu). They are also available through GLERL to users of the NOAA CoastWatch network (Leshkevich et al., 1995) in the Great Lakes region.

4.3.4.5 Evaluation of results

Calibration and assessment of the forecasting system are ongoing tasks. Daily average water surface temperatures computed by the model during 1993 for two points in Lake Erie are shown in Figure 4-7 along with water temperature measurements from two semi-permanent weather buoys moored at these locations. Also shown is the average deviation from the daily mean at each hour of the day at the two locations. The model tends to underestimate surface temperature in the spring (Julian Days 130-150), but correctly simulates peak surface temperatures of 23-25° C in the summer. The early fall cooling (Julian Days 260-280) at buoy 45132 is more

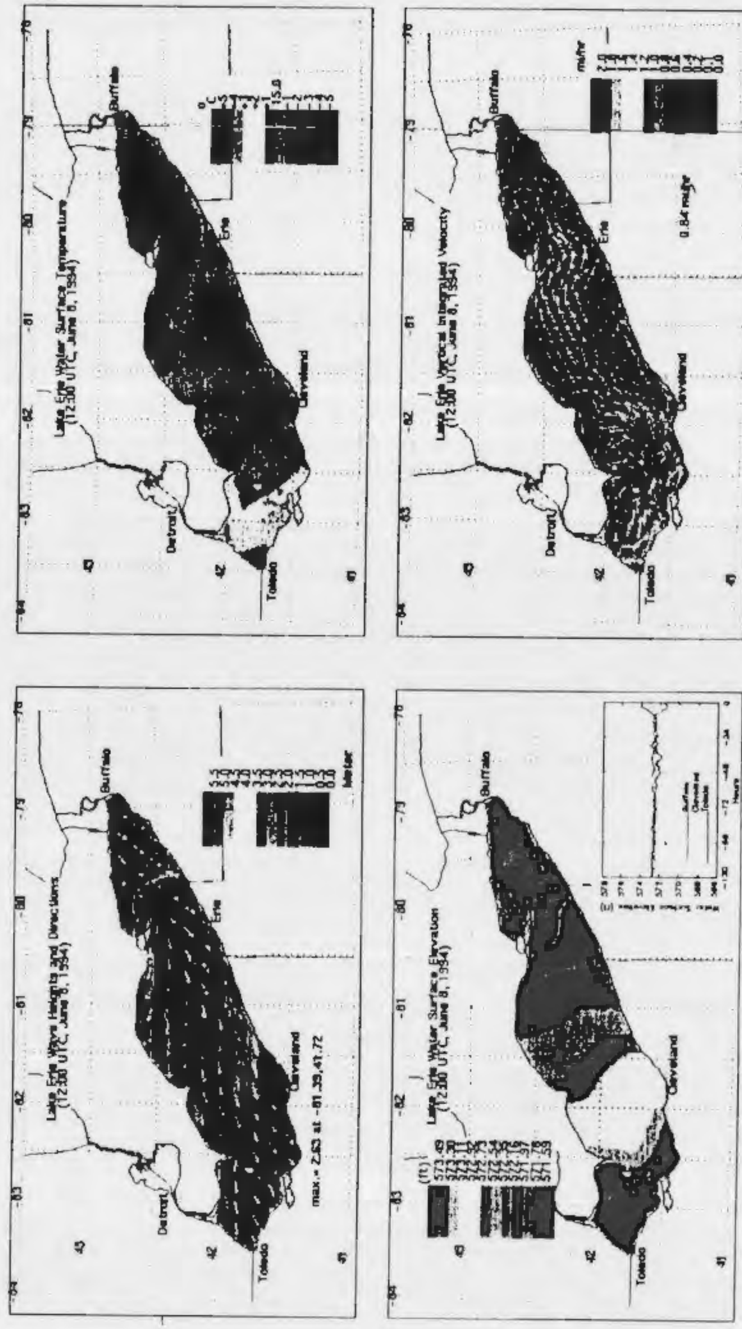

Figure 4-6. Sample product maps of wave height and direction, water surface elevation, water surface temperature, and vertically integrated velocity on June 8, 1994 (Schwab and Bedford, 1995).

rapid than the model simulation, but again the model recovers in the late fall. The average diurnal surface temperature fluctuation at the two buoys is matched quite well in both amplitude and phase by the model simulations. In summary, the comparison shows that the model is able to reproduce observed surface water temperatures with reasonable fidelity in Lake Erie, although the reasons for some discrepancies in the spring and fall need to be investigated further.

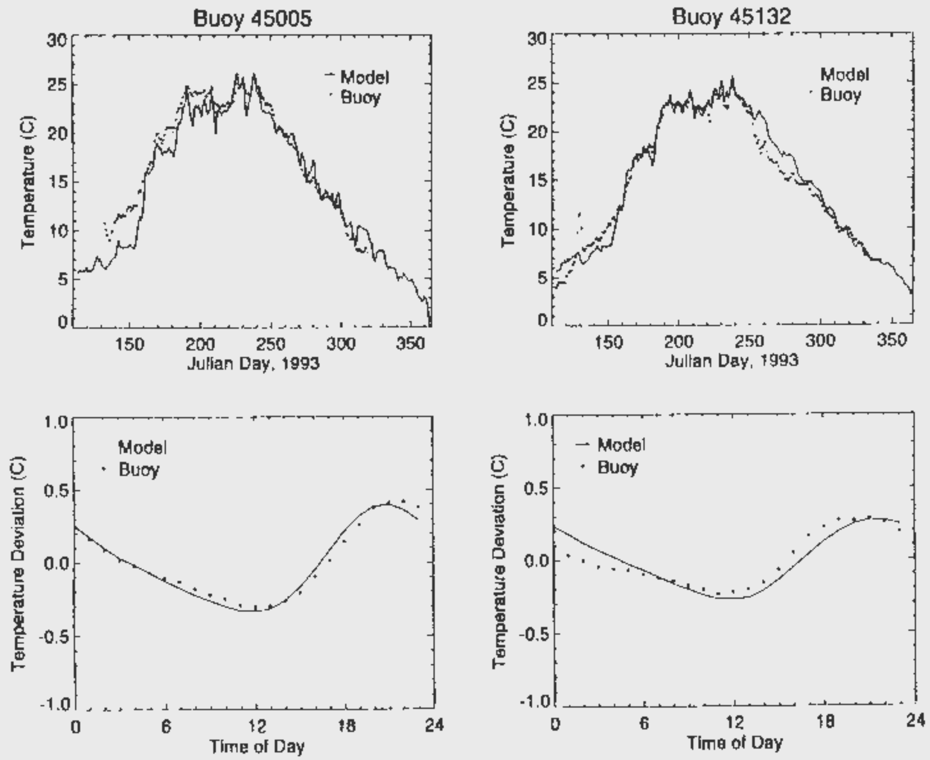

Figure 4-7. *Comparison of observed (dots) and nowcast (line) water temperature at two locations in Lake Erie during 1993. The upper panel is the daily mean temperature, and the lower panel is the average deviation from the daily mean for each hour of the day (the diurnal cycle) (Schwab and Bedford, 1995).*

4.3.4.6 Plans

The initial implementation of the system produces daily nowcasts and 24 hour forecasts of water level fluctuation, temperature, and circulation for Lake Erie. Full implementation of the system will include: 1) extension to all five lakes, and 2) input from meteorological forecast models to provide 2-day forecasts of lake conditions.

4.4 LONG-TERM VARIABILITY

In this section we will consider circulation patterns over significantly longer time scales: from seasonal to climatic scales. As we have seen, lake circulation can change dramatically on shorter time scales, but it is still possible to find more persistent circulation patterns on longer time scales. This expectation comes from the fact that unlike highly irregular weather events, regular seasonally changing atmospheric forcing can generate more stable average circulation patterns.

4.4.1 Observed summer, winter, and annual circulation in the Great Lakes

In order to assess the impact of potential climate change (whatever the reason for these changes) on lake circulation, it is necessary to assess our present knowledge of lake circulation climatology. "Climatology" typically assumes averaging over 30 or more years of continuous observations. Unfortunately, as we approach the low-frequency band of current spectrum, we are entering the area where less and less observational data are available, and that makes prediction of the long-term changes in large-scale circulation especially difficult. For example, one can find samples of summer or winter circulation observations in each of the Great Lakes (Table 1), samples of annual circulation observations in most of the lakes, but much less data for the assessment of interannual variations. Here, winter and summer circulation have a special meaning because we will associate these seasons with two major dynamical regimes: stratified (roughly May-October) and isothermal (roughly November-April) periods. This type of averaging was adopted in previous studies of circulation in Lake Ontario (Pickett, 1980; Saylor et al., 1981; Murthy and Schertzer, 1994), and Lake Huron (Saylor and Miller, 1979).

In fluid mechanics there are two approaches to study circulation: Eulerian, where time series of observations at fixed points are used, and Lagrangian, where trajectories of moving particles are used. Historically, the latter approach was the first employed both in oceanography and limnology. Drifting ships or drift bottles naturally indicated the movement of the surface layers. The first map of the surface currents in the Great Lakes (Figure 4-8) was presented by Harrington (1894) who used observations of drift bottle movements during the ice-free seasons of 1892-93. Although the Lagrangian approach was extensively used later in Lake Erie (Olson, 1950; Wright, 1955; Verber, 1953, 1955; Hamblin, 1971; Saylor and Miller, 1987), Lake Superior (Rushmejer et al., 1958), Lake Huron (Ayers et al., 1956), Lake Michigan (Ayers et al., 1958; Ayers, 1959; Johnson, 1960; Van Oosten, 1963; Monahan and Pilgrim, 1975; Pickett et al., 1983; Clites, 1989), and Lake Ontario (Casey et al., 1966; Simons et al., 1985; Masse and Murthy, 1992), there has been no attempt to update Harrington's map. Moreover, no observation-based winter circulation map covering all Great Lakes has been presented. There was one attempt to derive winter circulation patterns in the Great Lakes based on the results of modeling (Pickett, 1980). Pickett presented only two observation-based winter circulation maps available at that time: Lakes Ontario and Huron. These observations employed the Eulerian approach.

Lake	Period	Reference	Long-term Modeling Exercise
Erie	1964-65	FWPCA (1968), Hamblin (1971)	
	Summer 1970	Blanton and Winklhofer (1972), Simons (1976a), Mortimer (1987)	Simons (1976a)
	1979-80	Saylor and Miller (1987)	Schwab and Bennett (1987), Kuan et al. (1994)
Huron	Summer 1966	Sloss and Saylor (1976a)	
	Winter 1974-75	Saylor and Miller (1979)	
Michigan	1962-1964	FWPCA (1967)	Allender (1977)
	Summer 1976	Saylor et al. (1980)	Allender and Saylor (1979), Schwab (1983)
	1982-83	Gottlieb et al. (1989)	Beletsky and Schwab (1998)
Ontario	1964-65	Casey et al. (1966)	
	1972-73	Saylor et al. (1981)	Simons (1974, 1975, 1976b), Bennett (1977), Huang and Sloss (1981)
	1982-83	Simons et al. (1985), Boyce et al. (1989)	Simons (1985), Simons and Schertzer (1989)
Superior	1966-67	Sloss and Saylor (1976b), IJC (1977)	
	Summer 1973	Sloss and Saylor (1976b), Lam (1978)	Lam (1978)

Table 4-1. *Inventory of major long-term current observations and modeling exercises in the Great Lakes.*

There was significant progress in long-term current observations in the past 10-15 years, especially in winter circulation studies, and we feel that there is a need to update our present knowledge of large-scale circulation. Therefore, we decided to produce new circulation maps in the Great Lakes (Beletsky et al., 1999) based on the most recent and comprehensive current observations in Lake Michigan (Gottlieb et al., 1989), Lake Erie (Saylor and Miller, 1987), Lake Superior (Sloss and Saylor, 1976b), Lake Ontario (Saylor et al., 1981), and Lake Huron (Sloss and Saylor, 1976a; Saylor and Miller, 1979). We edited some existing circulation maps (mostly by overlaying current vectors on the existing circulation maps or vice versa) to have a similar set of maps for each lake describing summer, winter, and annual circulations. For example, we overlayed mean currents on the existing Lake Huron summer circulation map presented in Saylor and Miller (1979), but we added circulation patterns to the existing map of Lake Huron winter currents (Saylor and Miller, 1979). We also overlayed mean currents on the existing Lake Superior summer circulation map (IJC, 1977). In the Lake Ontario case, we made a new annual circulation map using IFYGL observations and added it to the existing summer and winter circulation maps (Saylor et al., 1981).

All observations that we used in this study differ from Harrington's data in two ways. First, we employed only the Eulerian approach, which is different from Harrington's Lagrangian approach. Second, while Harrrington's data describe surface circulation, we present only subsurface currents (the minimum depth of observations in the whole data set is 6 meters). This should be kept in mind, because surface currents depend much more significantly on wind forcing than currents in deeper layers, and, therefore, may not be representative of the depth-averaged currents, especially in summer.

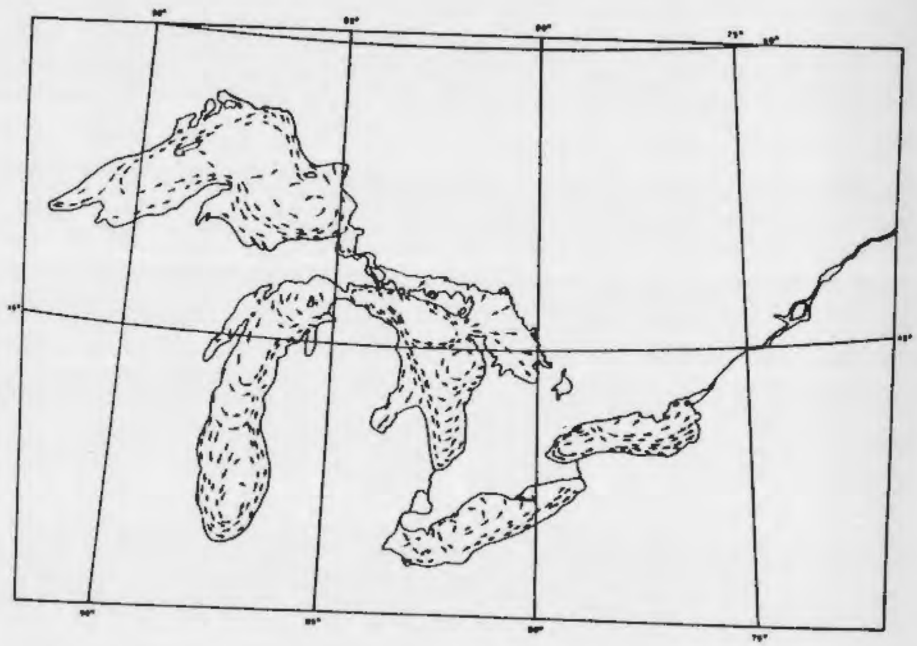

Figure 4-8. *Surface currents in the Great Lakes (Harrington, 1894; Liu et al., 1976).*

4.4.1.1 Summer circulation

Observations of summer circulation are generally more abundant than those of the winter circulation. The oldest observations of lake circulation (Harrington, 1894) are also for the summer period. Observations have shown that the summer circulation pattern is mostly cyclonic in Lakes Huron (Figure 4-9), Michigan (Figure 4-10), Ontario (Figure 4-11), and Superior (Figure 4-12), which is generally consistent with

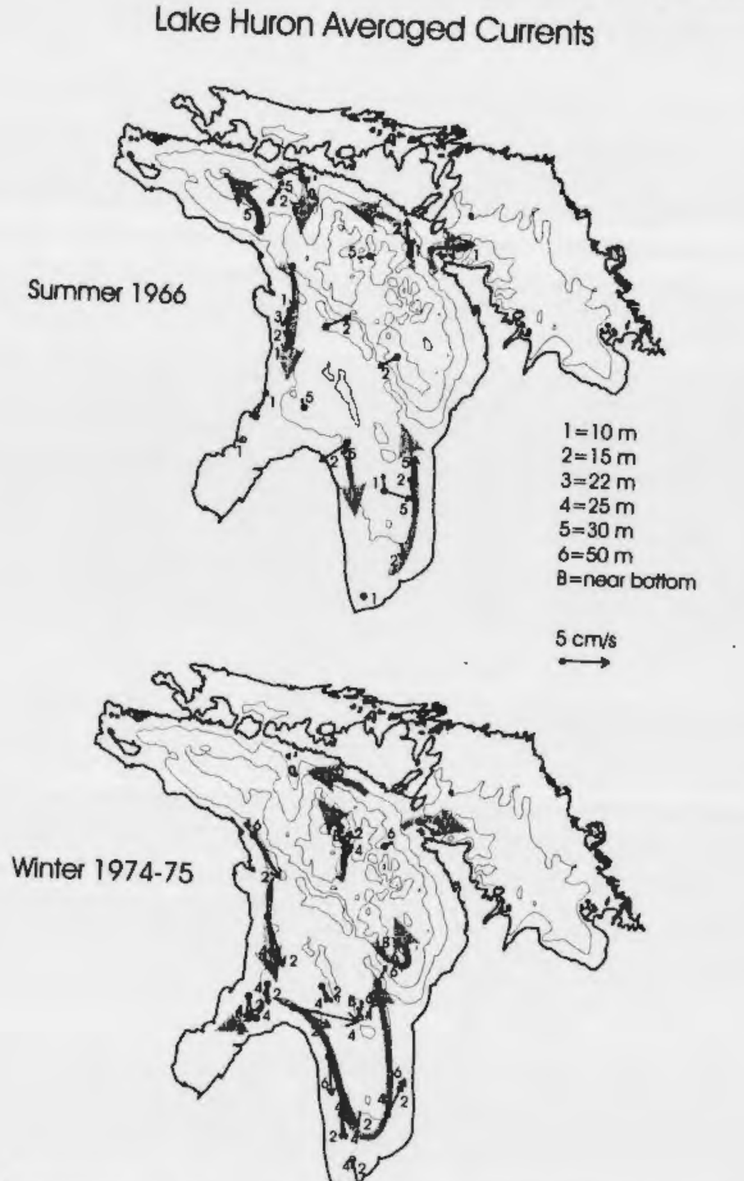

Figure 4-9. *Summer and winter circulation in Lake Huron (Beletsky et al., 1999).*

Harrington's data and with the density-driven one-gyre circulation concept. In Lake Erie (Figure 4-13), circulation represents a combination of the main anticyclonic gyre and a smaller cyclonic gyre in the central basin, which is different from Harrington's observations. The magnitude of summer circulation is several cm s^{-1}. The strongest mean summer currents, up to 7 cm s^{-1}, were observed near the tip of the Keweenaw Peninsula in Lake Superior (Figure 4-12). Currents typically change their direction with depth, and their speed decreases, which reflects the importance of baroclinic effects in the presence of the seasonal thermocline.

Interannual variability of the summer circulation has not been systematically studied in any of the Great Lakes, although there are some indications that summer circulation can vary from year to year. Therefore, the maps presented here should be considered primarily as examples of individual seasonal patterns, not as climatology. Nevertheless, some features of summer circulation appear to be very stable, namely the eastward current near the south shore of Lake Ontario observed both in 1972 during IFYGL (Saylor et al., 1981) and 10 years later in the 1982 experiment, (Murthy and Schertzer, 1994). The Keweenaw current is a persistent feature of summer circulation in Lake Superior (Ragotzkie, 1966; Sloss and Saylor, 1976b).

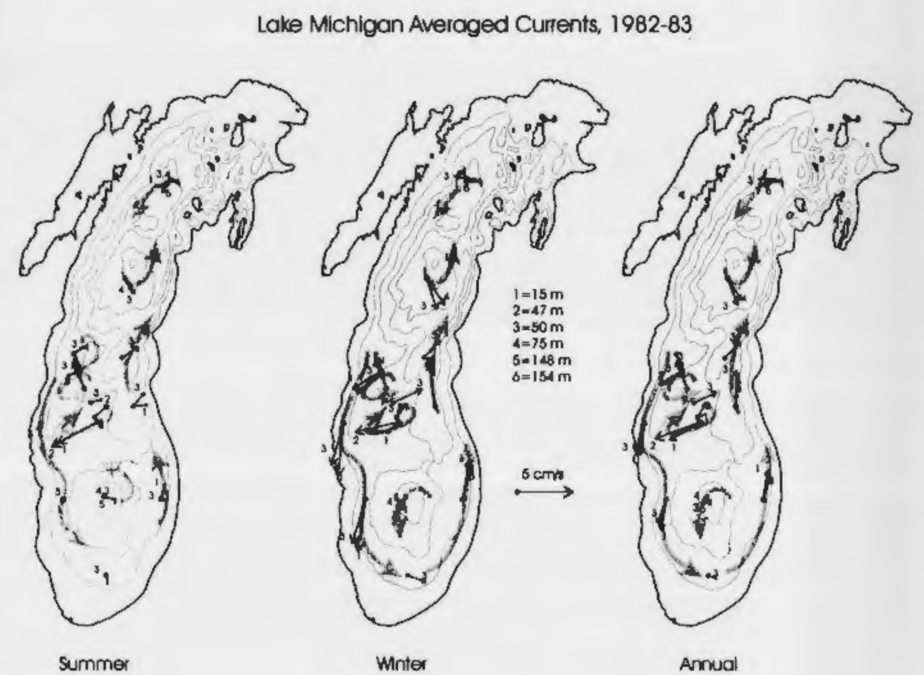

Figure 4-10. *Summer, winter and annual circulation in Lake Michigan (Beletsky et al., 1999).*

Lake-wide cyclonic circulation observed in 1967 (Sloss and Saylor, 1976b) was similar to the one observed in 1973 (Lam, 1978) although Lam (1978) reported much higher velocities. Westward flow in the open part of central Lake Erie in 1963 (Hamblin, 1971) was similar to the 1979 flow (Figure 4-13). In addition, a combination of an anticyclonic gyre and a cyclonic gyre in central Lake Erie was observed in both 1970 (Simons, 1976a) and 1979 (Figure 4-13).

In the Lake Michigan case, neither FPWCA (1967), nor Saylor et al. (1980) provide maps of summer circulation for 1963 or 1976, but their description and published data make it clear that the circulation becomes increasingly cyclonic in the end of the stratified period, which coincides with more recent observations (Figure 4-10). Cyclonic circulation in central Lake Ontario in 1972 (Saylor et al., 1981) was similar to the 1982 cyclonic circulation (Murthy and Schertzer, 1994). On the other

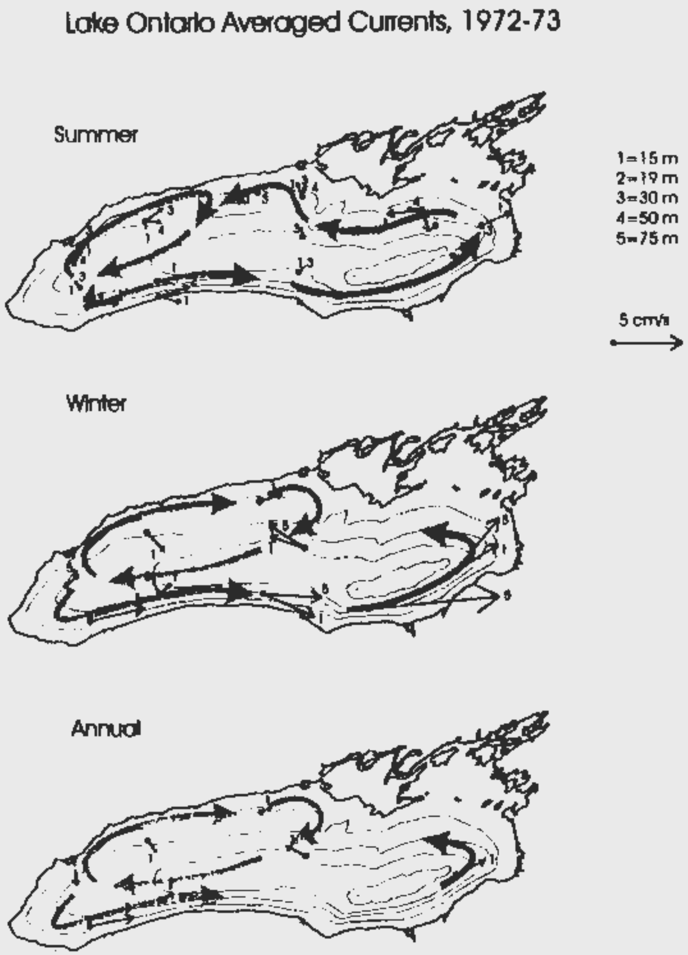

Figure 4-11. *Summer, winter and annual circulation in Lake Ontario (Beletsky et al., 1999).*

hand, the circulation pattern in western Lake Ontario was different in different years: it was cyclonic in 1965 (Casey et al., 1966) and anticyclonic in 1972 according to the IFYGL observations (Figure 4-11).

4.4.1.2 Winter circulation

Sufficient observational data are now available to describe large-scale winter circulation in all of the Great Lakes except Lake Superior, where observations covered only western part of the lake (Figure 4-12). Winter circulation is stronger than summer circulation because of the stronger winds in winter. The strongest mean winter currents were observed in southeastern Lake Ontario (Figure 4-11), up to 10 cm/s. Winter currents are essentially barotropic, which means that their variations with depth are minor, especially in comparison with summer currents. Cyclonic circulation persists in the winter both in Lake Huron (Figure 4-9) and in Lake

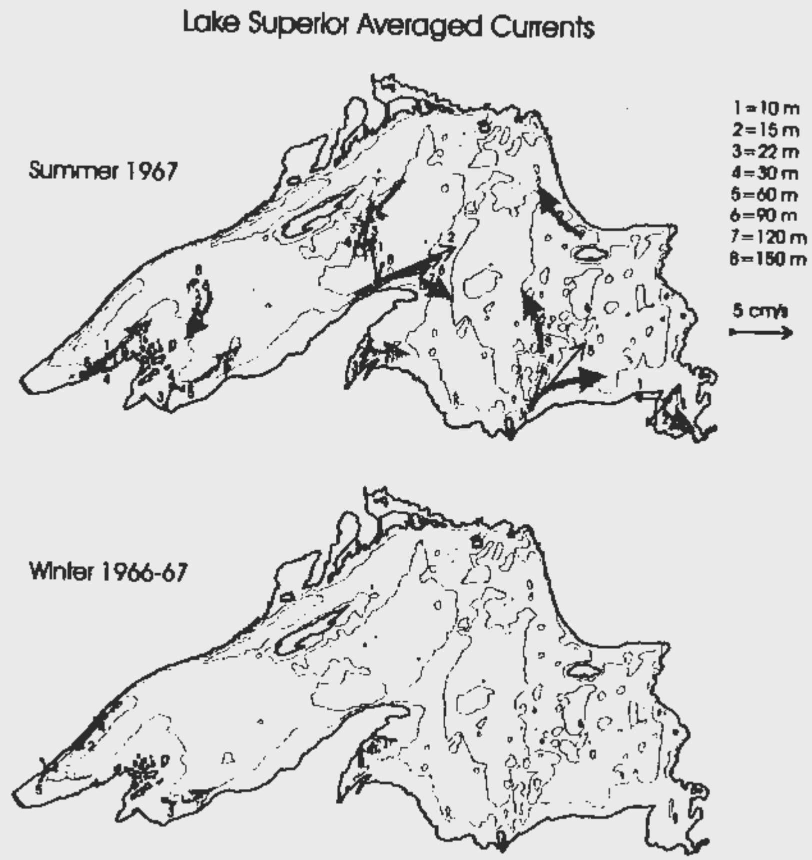

Figure 4-12. *Summer and winter circulation in Lake Superior (Beletsky et al., 1999).*

Michigan (Figure 4-10), where it is even more cyclonic than in summer. This can be attributed to the regional lake-induced cyclonic vorticity in the atmosphere in winter (Petterssen and Calabrese, 1959). Lakes Erie (Figure 4-13) and Ontario (Figure 4-11) reveal two-gyre winter circulations.

Again, some interannual variations are possible. The IFYGL observations in Lake Ontario revealed a two-gyre winter circulation pattern in central Lake Ontario during the winter of 1972-73 (Saylor et al., 1981), and a one-gyre pattern during the 1982-83 winter (Simons et al., 1985). Other features, on the other hand, are very stable. Thus, winter circulation in Lake Michigan was cyclonic during both 1962-63 (FWPCA, 1967) and 1982-83 (Figure 4-10) winters. Strong eastward current was observed near the south shore of Lake Ontario both during the 1972-73 winter

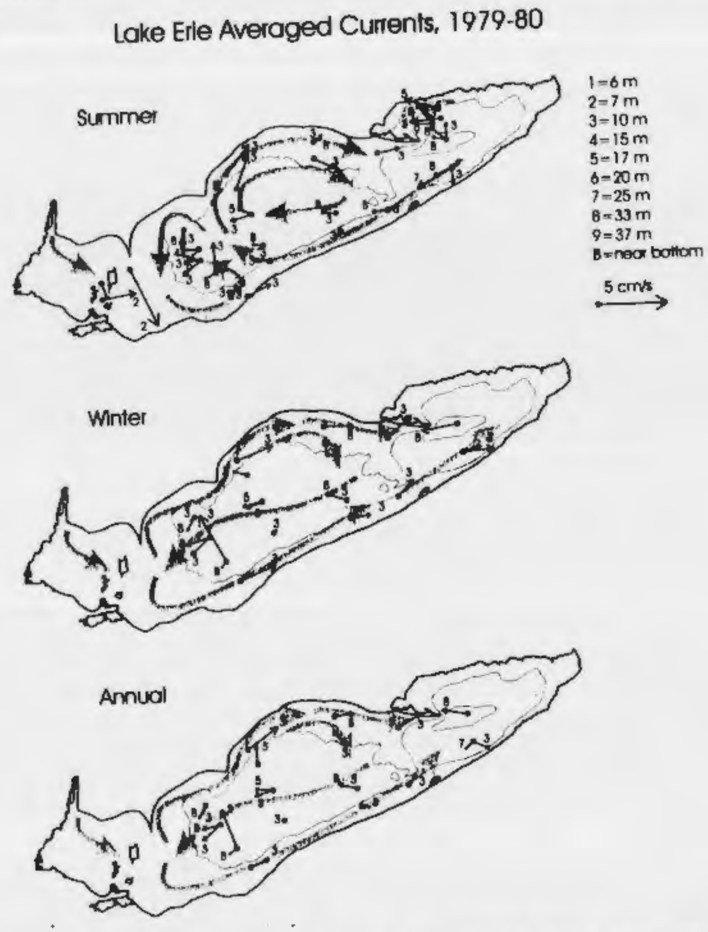

Figure 4-13. *Summer, winter and annual circulation in Lake Erie (Beletsky et al., 1999).*

(Saylor et al., 1981) and the 1982-83 winter (Simons et al., 1985). Westward flow in the open part of central Lake Erie during the 1964-65 winter (Hamblin, 1971) was also persistent during the 1979-80 winter (Saylor and Miller, 1987). In fact, these westward currents generally do not change direction over the whole year.

4.4.1.3 Annual circulation

We can only consider describing the annual circulation in Lake Erie, Lake Michigan, and Lake Ontario because they are the only lakes with sufficient observational coverage (Table 1). In all lakes, winter circulation appears to be stronger than summer circulation, and, therefore, the annual circulation pattern essentially repeats that of winter. It is cyclonic in Lake Michigan (Figure 4-10), and it has a two-gyre pattern in Lake Erie (Figure 4-13) and in Lake Ontario (Figure 4-11). Interannual variability of the annual circulation has probably never been investigated before because of the lack of long-term observations anywhere except the open parts of central Lake Erie and Lake Ontario. Earlier observations in Lake Ontario (Casey et al., 1966) and Lake Michigan (FPWCA, 1967) had sufficient duration, but annual circulation maps based on these data were never made to the best of our knowledge. The 1982-83 observations on the north-south transect of Lake Ontario (Boyce et al., 1989) showed cyclonic flow during both summer and winter, which makes annual circulation in this area also cyclonic, which is different from the two-gyre annual circulation during 1972-73 (Figure 4-11). Alternatively, year-long observations made in different decades in central Lake Erie (Hamblin, 1971; Saylor and Miller, 1987) showed a similar westward flow in this area. More studies are needed to address this question in other lakes.

4.4.2 Lake-wide circulation modeling

4.4.2.1 Barotropic models

Since the arrival of 2-d barotropic models, there were attempts to estimate mean winter circulation as the steady-state solutions of these models for a specified mean wind (Rao and Murty, 1970). They were successful in some cases. Pickett (1980) presented results from the 2-d model of Lake Ontario which coincided with the observed two-gyre winter circulation patterns during IFYGL. Later, Simons (1985) showed the importance of time-dependent modeling in producing the mean cyclonic circulation in Lake Ontario during the winter of 1983. Schwab (1983) simulated barotropic circulation in Lake Michigan for 8 months in 1976.

4.4.2.2 Early baroclinic models

Three-dimensional modeling of lake circulation and thermal structure for periods exceeding several months have been very rare in the past. One limiting factor is obviously computer power. One also needs good meteorological data to force the model. Finally, the number of long-term observations appropriate for model calibration and evaluation is limited as follows from the Table 1. Therefore, the most comprehensive modeling studies correspond very closely with significant observational programs, except for the Lake Huron data set, which has not been used by modelers to the best of our knowledge.

The first long-term 3-d modeling was done by Simons (1976b). Using numerous meteorological and hydrological observations obtained during the IFYGL, he simulated Lake Ontario circulation for the whole IFYGL period (1972-1973). The temperature field in this model was not calculated; it was based on the weekly temperature surveys, and, therefore, this type of model is more similar to the earlier described diagnostic models. Later, Simons used a similar approach for Lake Erie circulation studies, from April to December 1970 (Simons 1976a), and Lam (1978) for Lake Superior circulation studies from June to September, 1973. These models were verified with available observations.

The first fully prognostic model (in oceanography a prognostic model often means a model where the temperature field is calculated, as opposed to a diagnostic model) was applied to Lake Michigan by Allender and Saylor (1979). The finite-difference grid was variable in all three dimensions, although it was rather coarse. It consisted of 24x16 grid points in horizontal, and 8 levels in the vertical. Nevertheless, they were able to simulate thermal structure in the lake from April to November of 1976. In particular, their model simulated such basic features of the thermal regime of Lake Michigan as thermal bar, full stratification, and autumn cooling. The atmospheric forcing in the model was rather simplified. Therefore, calculation of currents showed only limited success when compared with observations. Additionally, upwelling near the western shore was apparently too strong.

Another prognostic model was developed by Astrakhantsev et al. (1988) for studies of the climatological thermal structure and circulation in Lake Ladoga. Their model uses climatological heat and momentum fluxes, and was run for 22 years to reach equilibrium. Again, the model resolution was relatively low with 17x16 grid points on the surface, and 16 levels in the vertical.

4.4.2.3 Modeling in the 1990's

Previously introduced in Sections 4.3.2 and 4.3.4, the Princeton model has been applied recently to two of the five Great Lakes: Lakes Erie and Michigan. Modeling in the 1990's is characterized by significantly increased computer power and improved meteorology. Therefore, Kuan et al. (1994) were able to use a uniform 2 km (209x57 grid points on the surface) horizontal resolution in their long-term modeling of Lake Erie. Vertical resolution was 14 levels. Temperature and current observations on a mid-lake transect of Lake Erie during summer 1979 were used for model evaluation. The model simulated rather realistically both currents and thermal structure during the 10-day period chosen for extensive evaluation.

In another study (Beletsky and Schwab, 1998), the Princeton Model has been applied to Lake Michigan to simulate daily, monthly, and seasonably variable thermal structure, circulation patterns, and water level in the lake. The model has 20 levels and a uniform horizontal grid size of 5 km (53x102 surface grid points). The model is driven with surface fluxes of heat and momentum derived from observed meteorological conditions at eight land stations and two buoys from April 1982 to November 1983. Three types of observational data are being used for the model verification: water level data from 9 gauges around the lake, surface temperature observations at 2 permanent buoys, and current and temperature observations during June 1982 - July 1983 at 15 and 50 m depth from 15 subsurface moorings. Besides being able to simulate the annual thermal cycle, the model also realistically simulated the intensification of cyclonic circulation in winter, which is a distinct feature of Lake Michigan hydrodynamics (Saylor et al., 1980).

4.4.3 Impact of climate change on circulation

Recently, several interesting predictions of long-term changes of the Great Lakes thermal structure due to the anticipated global warming were made (Schertzer and Sawchuk, 1990; McCormick, 1990; Boyce et al., 1993) by means of one-dimensional modeling. Their results demonstrated sensitivity of the thermal structure to climatic changes and dependence on different scenarios and differences in atmospheric general circulation models (GCM). What can we say about potential changes in large-scale lake circulation in response to climate change? Obviously, several conditions should be met before we can address that question properly, and the first one is that we need to know current climatology as a reference for all future changes. The interannual variability of lake circulation is also of great importance. Secondly, if we want to use a numerical hydrodynamic model in our predictions, we need to know boundary conditions (initial conditions will not be that important in this case). And thirdly, we have to prove the reliability of this hydrodynamic model. Let us address these questions starting with a question of current climatology.

If we compare the number of observations of currents and temperature in the Great Lakes, we will see that the former is much lower than the latter. But even for temperature, we probably have enough data to derive climatology only for the surface temperature and at several dozen water intakes around the lakes. It is even worse with currents because we have only one, sometimes two sets of reliable long-term observations for each lake. Therefore, as we emphasized in section 4.4.1, the summer, winter, and mean circulation patterns depicted in Figures 4-9 to 4-13 are not a climatology, but only a representative sample. Although they may be representative of climatology, we do not have enough observations to prove this. Unfortunately, we do not expect rapid growth of long-term observations in the future.

The second prerequisite is a knowledge of forcing functions, i.e. heat and momentum fluxes. Theoretically, we can already use an atmospheric GCM output to run a hydrodynamic model for 30 years with predicted meteorological fields in order to obtain a new current climatology (here we assume that our hydrodynamic model is accurate enough). Unfortunately, the reliability of GCM predictions, in particular wind field predictions, is questionable at the present time. In addition, the existing GCM's have too coarse a spatial resolution (up to 300 km) to provide an accurate description of the regional meteorology (see Chapter 2) and may not resolve some important details, especially in the wind field. We can, however, expect more detailed predictions of local climates in the future.

Finally, consider the reliability of long-term hydrodynamic modeling. In the past, there were only a few results reported in this area. Recently, there were some preliminary encouraging results (Kuan et al., 1994; Beletsky and Schwab, 1998), although more extensive testing of circulation models is needed.

What can we do in the meantime? Under the conditions when only slow growth of new large-scale current observations is anticipated, the main focus will naturally be on modeling. Thus, it is already possible to start recreating current climatology on the basis of circulation hindcasts using existing meteorological archives. Moreover, we will also have more and more current simulations as GLFS nowcasts continue in the next century. For example, for Lake Erie, the model output can be used to accumulate long-term statistics of currents and temperature since 1993, so it will be possible in the future to derive lake currents and temperature climatology based completely on the model results. Of course, one has to remember that statistics derived from model results are only an approximation of statistics derived from observations.

As an alternative to the use of GCM forcing, it might also be appropriate to use circulation patterns calculated for extremely warm or cold years as analogues of circulations corresponding to warmer or colder climates. A somewhat similar approach was recently suggested by Schertzer and Sawchuk (1990) in the one-dimensional modeling of the thermal structure in Lake Erie.

What can we say about potential circulation changes in the meantime, if we set aside numerical modeling and try to use only general knowledge of lake physics? Let us use a global warming scenario as an example. We know that all GCM's predict milder winters which lead to longer stratification periods (see Chapter 3) and less ice cover (McCormick, 1990). They also predict a decrease in the wind speed, and a decrease in the water level because of changes in evaporation (Croley, 1994). Consider the speed of currents first. We know that the amplitude of currents is proportional to wind speed and density gradients, and inversely proportional to depth. Therefore, an increase in the duration of the stratification period will increase the duration and amplitude of the density-driven currents. In addition, a decrease in ice cover during warm winters will increase transfer of momentum from wind to currents. The decrease of water levels should also increase current amplitude, especially in the shallow regions. Alternatively, the decrease in wind speed should also decrease current amplitude, and therefore, these changes may eventually balance each other. Finally, consider potential changes in circulation patterns. Unfortunately, we can say even less about the circulation patterns as compared to the current speed. We saw earlier that circulation patterns were different depending on the lake and season. At the moment, the physical mechanisms that are responsible for mean circulation are not well understood. Therefore, we may assume that the circulation pattern changes may be different in each particular case.

4.5 CONCLUSIONS

Here we summarize briefly where we stand, and where we go from here. We saw that for the majority of large-scale short-term dynamic processes, both waves and circulation, basic physical mechanisms are generally understood. For some processes, like storm surges and seiches, existing models can even predict their development with a high degree of accuracy. The prediction of temperature and circulation is less accurate, especially in summer when circulation is well predicted mostly during the periods of storms when the wind influence is prevalent. This is due to inadequate horizontal resolution in models, accuracy of forcing functions, adequacy of model physics, and also due to sensitivity to initial conditions. We expect improvements in summer circulation modeling in the near future due to further grid refinement in lake-wide circulation models. This will allow us to better describe such processes as coastal upwelling fronts and coastal jets, thermal bar, internal waves, and mesoscale eddies. Accurate simulation of these processes is also necessary for reliable estimates of offshore-nearshore transports.

Nested grid finite-difference or finite-element modeling will also be important because some important physical processes will need a resolution higher than in the lake-wide circulation models. Extension of the Great Lakes Forecasting System to all five lakes will also make it possible to provide open boundary conditions for high resolution operational nowcasts and forecasts of any limited coastal areas. From the point of view of model physics, we can expect refinement of turbulent parameterization schemes allowing better simulation of the thermocline dynamics. New observational data, for example, cloud cover from the GOES-8 satellite, and refined meteorological model forecasts will result in further improvement of the accuracy of the surface boundary conditions.

One important question is current climatology. We need more long-term observations to assess climatological circulation and interannual variability. Under the condition that only a few new large-scale current observations will be available, the main focus will obviously be on the modeling. Thus, it is already possible to start creating climatology on the basis of the Great Lakes Forecasting System nowcasts, or on the basis of circulation hindcasts using meteorological archives.

Another important issue for freezing lakes is the influence of ice on lake hydrodynamics. Nothing was said here about that problem, because currently there is no modeling activity in that area, although we know that ice can significantly modify coastal currents by decreasing the transfer of momentum from atmosphere to water. Incorporation of ice into the annual cycle in numerical models is also important from the point of view of accorate simulation of total heat budget of a lake. The development of coupled ice-circulation models will be an important achievement in winter thermal structure and circulation modeling.

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